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## GBOT - one year before Gaia's launch

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### Introduction

GBOT (Ground Based Optical Tracking, [1]) is a part of the Gaia satellite mission, which is being set up to be able to fully exploit the capabilities of the satellite, even for the best measured stars. The GBOT project consists of about half a dozen small (1-2 m class telescopes), which will make daily observations of the Gaia space craft. From these data, the GBOT group will derive astrometric positions, which will be used in the reconstruction of Gaia's orbit.

### 1. Why do we need GBOT?

The main reason for the creation of the GBOT project, are effects which have a detrimental effect on the accuracy of astrometric observations such as those Gaia will be performing. These are mainly the aberration caused by the transversal motion of the observing platform<sup>1</sup> affecting the accuracy of measurements of stellar positions, and for the much closer solar system bodies, the baseline of parallaxes.

Aberration is a huge (30'') effect, caused by the movement of the detecting device (i.e. Gaia or also the Earth) in respect to the observed objects. In order to correct for aberration one needs to precisely know the motion of the detector to some reference, usually the solar system barycentre. The effect is small in small field astrometry, since the displacement of the objects is almost the same - something which is no longer true for whole sky astrometry. However for previous whole sky missions, such as Hipparcos, conventional means to obtain the spacecraft's 3 dimensional motion were sufficiently precise to push the effect of residual aberration far beyond the nominal precision of the astrometry. This is still valid for most stars observed by Gaia, however those which will be measured best, i.e. the bright, well observed stars brighter than  $G=15$  mag require a more accurate knowledge of the satellite's motion than the conventional methods via one radar tracking station can deliver.

While solar system objects are not the main objective of Gaia, it is an important aspect - Gaia will discover many new asteroids, some of them being Near Earth objects, in some cases with the potential to cross Earth's orbit. In order to measure precise enough parallaxes ( $\sim 1''$ ) the baseline needs to be known to a high degree of precision, i.e. the position of Gaia needs to be measured very well and continuously. Mainly for these two reasons GBOT was conceived. The commitments of GBOT are to deliver one measurement<sup>2</sup> precise to 20 mas each day (period of 24 hours). The systematic error (accuracy) of the

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<sup>1</sup>Aberration would affect all observations, whether they are done on a moving planet, e.g. Earth, or a moving space craft, such as Gaia. For small field astrometric observations as those usually done with ground based telescopes, the aberration is not of much concern, since the effect influences the positions of all objects in a small field, producing the same shift of all objects, which is therefore not of relevance. For a whole sky scanning mission, like Gaia, with two FOV's having an angle between them, the aberration, which can amount up to more than 20'' is a major problem and needs to be taken care of accordingly.

<sup>2</sup>or rather sequence of measurements - GBOT will deliver every measurement; since the apparent trajectory of Gaia is not a straight line, the individual measurements of a sequence cannot be averaged without some loss of accuracy.

measurements needs to be even smaller. We need to point out, that these levels of accuracy are not achievable today, with the current reference catalogue material, but only with using astrometry from Gaia itself - today we can only expect to reach 50 - 100 mas.

## **2. Requirements - which facilities are suitable for GBOT?**

In order to achieve its goal, GBOT requires a small network of about half a dozen telescopes of the 1-2 m class, distributed all over the world. Since the L2, i.e. roughly the location of Gaia (which oscillates on a Lissajous-orbit around the L2) always lies on the ecliptic opposite the Sun, GBOT needs telescopes on both hemispheres, and more than one, to be less dependant on weather conditions at one site, especially since in most location, the weather conditions are more inclement during winter which is the geometrically more favourable observing season.

GBOT has requirements concerning the telescopes/instrumentation, which are:

- Telescope of the 1 - 2 m class. The telescope should be able to regularly make contributions, i.e. observations, ideal are robotic telescopes, or telescopes with long term observing programs.
- CCD detector (monolithic or part of a mosaic) which has a FOV of at least  $5' \times 5'$ , and a image scale of better than  $0.4''/\text{pix}$ , somewhat depending on the quality of the site's seeing. As a compromise between depth and severity of differential colour refraction red light filters have been chosen as preferable.
- Further secondary requirements include: precise clocks, well known geographical coordinates of telescope, sufficient connection to the Internet in order to download data, etc.

## **3. The challenges of GBOT - and where the project stands today**

The GBOT team faces several challenges:

- To recruit observatories willing to participate and to set up a small network of 1-2 m class telescopes.
- to determine and test observational procedures, which lead to obtaining the data needed.
- To develop a software pipeline which can cope with data material from highly diverse sources, and is able to derive high quality astrometry.
- To set up a database organising and storing the data, ensuring the dataflow from observatory to the receiving agency, especially keeping in mind that reductions need to be redone more than once, to secure the according hardware infrastructure to maintain such a database system.
- To coordinate a team of astronomers located in different locations.

The following part gives an overview of these challenges and how they are addressed today, less than one year before the launch of Gaia.

### *3.1 Telescope recruitment*

This has proven to be a rather difficult task, even if the willingness to help with such a high profile project, such as Gaia is high. However many observatories are facing unsure futures, some are even threatened with closure<sup>3</sup>. Another difficulty is the fact that many traditional observatories are organised in the

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<sup>3</sup>Observatory Hoher List has regrettably been closed down - a big loss and a missed opportunity not only because of GBOT, but also to commute astronomical research to the general public and students in particular. It is only to be hoped that all possibilities however slim, are used to save this observatory

conventional way by distributing observing time to visitor observers who have prior written a project proposal. This means that a campaign demanding daily observations such as GBOT necessarily has to interfere with a visitor's observing program, and in most cases even requiring the visiting astronomer himself to conduct observations for GBOT. Therefore robotic telescopes are much to be preferred, since they operate via queue observing and moreover automatically with minimal human interaction during the night. Another viable option are those non-robotic facilities operating in queue mode, or being used for long term projects, i.e. those with dedicated observers. Fortunately the number of suitable robotic telescopes has grown over the past few years and continues to do so.

At current GBOT is in negotiations with two institutions with robotic telescopes, one of them, Las Cumbres Optical Global Telescope Network (LCOGT, <http://www.lcogt.edu>) currently setting up a worldwide network of 1 m telescopes. This means that together with the second, the 2 m Liverpool telescope, which has thusfar provided the bulk of our test data, they will be able to provide the backbone of the GBOT network, enhanced by a few conventional telescopes. We are also projecting the 1.2 m Euler telescope on La Silla, the 1 m Pic du Midi and the VST on Paranal to join GBOT, several other institutions are still testing.

Therefore despite the rather dire onset, GBOT is actually in good shape and will be once the two main contributors have finally been secured be able to operate. However it must be pointed out that the recruitment is an ongoing task, and will continue until the end of Gaia's operations. Should a reader of this paper have a facility at his disposal which could be of interest to GBOT, please feel free to contact the coordinator of GBOT, M. Altmann under [maltmann@ari.uni-heidelberg.de](mailto:maltmann@ari.uni-heidelberg.de) and ask for the GBOT information leaflet. There are other groups within the Gaia project, such as GAIAFUN-SSO, and Gaia Science Alerts, which depend on the acquisition of ground based data during the operational phase of the mission. In order to aid each other in finding the required telescopic resources, GBOT has close contacts to these groups.

### 3.2 *Astrometric reduction pipeline software*

From the very beginning it was decided to develop own software rather than to rely on available products. The key reason for this is to have total control, understanding and influence over the code, and to avoid "black boxes". Software development began in 2009 and has reached a level of completion so that it is fully operable [3]. Nonetheless the pipeline gets continuously refined. Currently a detailed documentation and manual is being written.

One challenge was that the software has to be able to ingest data from very diverse sources, with large variations in the number and names of available FITS-keywords. This has been solved by an routine called `headermodif` which reads the header of each incoming file and writes all relevant header information into special GBOT FITS keywords.

Next in line is a program called `findsources` which does the source detection and extraction using various user-selectable algorithms. `astroredc` performs the astrometric reduction using a reference catalogue and the detected objects, sans the moving target. Apart from some other auxiliary programs, which make plots and graphs, etc. the final step is done with `targetfinder` which extracts the target, again with various options for the extracting algorithm, and determines the position of the moving target object. These components are all operational and have been used for quite some time - currently the main effort is apart from documentation, and diagnostic output. The GBOT pipeline has also been used for other purposes than GBOT, in one case a Kuiper-belt object was found.

### 3.3 *The database*

Having to store and maintain a rather large set of data from diverse sources justify the need of a dedicated database system. It was decided to develop the database on the basis of a SAADA type database ([2]). Database development started in 2011, and currently the database is operable, but still needs some development in some aspects. The database will receive, ingest and store all data, and available metadata, such

as reduction logs, ephemerides, etc. The reduction software can be run from the database, and results can be extracted into the formats required for delivery to ESOC.

Another very important reason for preferring a full-fledged database system over other kinds of storage philosophies is that, because due to the inadequate existing reference catalogue material, initially GBOT cannot reach its targeted astrometric quality; Therefore the astrometric reductions of *all* data collected to the time when Gaia astrometry has become available have to be repeated in an automated batch mode. A final reduction of all data will be done after the operational phase of Gaia to ensure maximum quality results. Additionally, as with all other parts of the Gaia project, all data and information used for GBOT must be archived so that it can be accessed later at any time, should the need arrive.

In terms of hardware, the main database will be located in Paris, with a mirror with less capability in Heidelberg. This mirror will mirror all the data plus provide the platform for daily operations should the main server in Paris fail. Having these servers in two different geographic locations helps prevent complete data loss in the event of a catastrophe.

### 3.4 *Tests, open issues, etc.*

Since 2009, several test campaigns have been conducted to establish and verify observational methods, with several telescopes, most importantly the Liverpool telescope, the 2.2 m telescope at La Silla, and the 1.2 m of the OHP, and the 1 m on Pic du Midi using the space craft WMAP and Planck as well as various asteroids. Most of these tests have been concluded, in effect showing that we are able to reach the level of precision we have committed ourselves to. Furthermore we have set up a suite of routine tests to evaluate the suitability of potential partner facilities.

One unknown issue in the game is still the brightness of Gaia. While we do have some hints from our observations of other spacecraft, especially WMAP, which overall has had a similar shape as Gaia, there are quite a few unknowns involved, and we will not know the brightness of Gaia until it has reached its final destination. Based on experience we are currently preparing for a brightness of  $R \sim 18$  mag, however we are aware that this could be off by more than a magnitude in either direction. Moreover in the hash environment in the L2-region the initially highly reflective Kapton mylar surfaces could degrade to become rough and essentially black, potentially drastically altering the reflective properties and thus the observed brightness of the probe with time. Overall this issue remains to be *the* most problematic unknown quantity for GBOT. In order to monitor the development of Gaia's brightness, observations from simultaneous multi passband photometers, such as BUSCA (Calar Alto) and/or GROND (La Silla) will have to be requested.

Far better known, but also a challenge is the fact that the Full moon is always in the vicinity of the spacecraft. Most telescopes will therefore not deliver useful data for a period of 3-4 days centred round Full moon<sup>4</sup>. We do however have a few telescopes, notably ESO's VST on Paranal, that allow us to observe quite close to the moon and yet achieve good results, this way possibly closing the gap to the Full moon night itself. Apart from this, a recent study by ESOC concerned with the reconstruction of Gaia's orbit, has revealed that small gaps in the coverage of GBOT observations can be tolerated. Therefore the Full moon gap is far less significant than previously thought.

While the measurement of the 3D coordinates of a telescope is straightforward nowadays with GPS, exact timing of the observing time is a challenge. The constraint here is 0.1 sec. Certainly most clocks today easily surpass this requirement. However an open question<sup>5</sup> is to which extent does the time listed as start of the exposure coincide with the actual opening of the shutter<sup>6</sup>?

Recently the GBOT group has compiled an assessment of all potential errors contributing to the overall error budget. It became clear, that this boils down to a couple of really dominating effects, currently the strongest spoiler is the quality of today's reference catalogue material. After the rereduction with Gaia

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<sup>4</sup>Also depending on the distance of Gaia from L2 at a given Full moon

<sup>5</sup>to be answered for every single partner facility

<sup>6</sup>Apart from the fact that a shutter has a finite opening and closing time too - something that needs to be taken into account, especially in the case of barndoor shutters

astrometry as reference the main contributors will be differential colour refraction. However all relevant error sources will be corrected so that the overall error stays below the 20 mas for a sequence.

#### 4. Radio-GBOT

A rather recent development is the idea to use the VLBI network of radio-telescopes to track Gaia. The signal from its communication and data-downlink antenna can be observed, and thus used to measure the state vector of Gaia. Since the "source" is bright, we do not need a VLBI network consisting of large telescopes. A network of medium to smaller size antennas would be sufficient. However this is nonetheless a major investment of resources, and measurements will not be possible every day; a frequency of once per week, or once or several times per month is much more likely. Thus on the one hand the coordinates (state vectors) of Gaia coming from VLBI measurements will be more accurate than the optical measurements, on the other the temporal density will be much lower. This means that the VLBI observations cannot replace the optical campaign, but will most likely prove to be a major enhancement, compliment and ultimate varification of the optical observations for GBOT, especially if the VLBI observations are well chosen and predominantly carried out at the times when Gaia crosses the celestial equator (and the reconstructed orbit is most sensitive to the transversal motion). Also, VLBI is not affected by the moon cycles.

The preparatory work for VLBI tracking of Gaia is conducted by the Joint Institute for VLBI in Europe (JIVE), involved in similar activities for a broad variety of space and planetary science missions. At present, the work concentrated on the evaluation of an optimal strategy of joint optical and radio observations in support to the Gaia mission. In particular, this includes test observations of operational spacecraft located in the L2 region. Special science-driven Gaia tasks that require the highest level of state vector determination are being investigated too.

Since radio observations of Gaia involve QSO's that form the International Celestial Reference Frame (ICRF) as reference sources, and these are very sparse, a denser fabric of secondary calibrators (typically - weaker in radio QSO's) is being considered. Due to the fact, that this approach was considered and started only recently, many aspects are still under study. Nevertheless, we are very confident, that Radio-GBOT will be feasible, and will provide valuable data for GBOT and thus the full exploitation of Gaia's potential. As a sidenote, GBOT most likely will need to change its name slightly to "Ground Based *Orbit* Tracking" from "Ground Based *Optical* Tracking", since that name would no longer be accurate.

#### 5. Operations and Deliveries

GBOT has the duty to obtain and analyse ground based imaging data of fields containing the Gaia satellite in order to derive astrometric positions of the spacecraft. The data will be observed by the committed partner observatories. In order to be able to operate these must know the position of Gaia, so that they can point their telescopes accordingly. On the other hand the results must be delivered to those who need them to reconstruct Gaia's orbit, namely the MOC (Missions Operations Control) team within ESOC (located in Darmstadt). This is done via an entity called SOC (Science Operations Control), located at ESAC near Madrid, through which all communication between GBOT and ESOC (MOC) will go. GBOT will receive orbital data from ESOC which will be transformed into ephemerides and supplied to the observatories. This way there is a two way flow of information/data from/to GBOT from/to ESOC and the observatories.



## 6. The Roadmap to Launch

As one of the Schedule Critical Items (at least partly) GBOT plays a significant role from very early in the operational phase of Gaia. It will kick in as soon as Gaia reaches its final orbit in the L2-region. Therefore GBOT participates in the series of operational rehearsals, which aim at testing and reviewing the orchestrated operation of all components of Gaia operations both during the initial commissioning phase and nominal operations. Four of these rehearsals are planned, each with a larger complexity and greater completion of the participating components. In the first one, in July 2012, GBOT took part only with the delivery of a data file. During the second one, actual data from one telescope will be taken, reduced and delivered, the third one, in late April 2013 will include more telescopes. By the fourth rehearsal the full readiness not only of GBOT needs to be demonstrated. Crucial for the functioning of GBOT is the dataflow as described in Sect. 5..

While, as described in this paper, GBOT is well advanced in all effects, and is shortly before operability, there still needs to be a lot done, such as documentation, fine tuning setting up of daily operations, etc. Many aspects, such as the software development to ever higher degrees of perfection will continue after the launch, even to the end of the operational phase. One thing needs to be made very clear: As noted before in this text, GBOT will at first not be able to reach the aims in terms of accuracy - only after about 2 years, when data from Gaia itself will be available, will GBOT reach its aims. This also means, that during that time all observations done before will need to be reduced again. After data taking is complete, a third round of reduction of all data will be carried out, to ensure the best possible reduction and analysis of the data. After that GBOT will come to an end.

## Conclusion

GBOT is a small but important part of the keystone Gaia project, which will have an enormous impact on our view of the Milky Way and the cosmos. GBOT will enable utilising the full potential of the Gaia measurements, even for the brightest best measured stars and objects of the solar system. Less than one year before launch, the GBOT team - like all other teams involved in the project - is working hard to obtain readiness for the initialisation of the active phase of Gaia. While a lot remains to be done, GBOT is well advanced and is confident to be fully operable when the date for the launch has come.

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